Digital contour of linear control in the pulse voltage stabilizer

S N Titovskii[1,2,3], T S Titovskaya[2], N V Titovskaya[1,2] and Z E Shaporova[1]

[1]Krasnoyarsk State Agrarian University, 90, Mira ave., 660049 Krasnoyarsk, Russia
[2]Siberian Federal University, 79 Svobodny ave., 660041 Krasnoyarsk, Russia

[3]E-mail: sntitovsky@rambler.ru

Annotation. This paper provides an analysis of the operation of the pulse voltage stabilizer with a digital control contour, which uses a linear correlation between power switch opening pulse duration and the output voltage deviation from the nominal one. The influence of the errors, caused by digital data representation, on the control loop output impulse duration was evaluated. The conditions that minimize the influence of these errors on the stabilizer operation are revealed.

1. Introduction

Nowadays, the sources of stabilized voltage are being used almost everywhere. When constructing such sources, developers prefer the pulse voltage stabilizers since, compared to linear stabilizers, they have indisputable and very significant advantages - this is a high efficiency, and, as a result, low heat generation, as well as low weight and small overall dimensions [1,2]. The applying of the digital control contour, instead of the analog one, in the pulse stabilizers eliminates the temperature and time drift of parameters, which is typical for analog circuits and is being a modern subject of study [3-5].

2. Analytical study

The model of the pulse voltage stabilizer contains some power nodes - a key, an inductance coil, a diode, a key control device and a reference voltage source [6, 7].

The key control device aimed to generate a key-opening pulse, which duration depends on the deviation of a measured output voltage from the reference voltage

$$T_{pul} = F(U_{cur}, U_{et}), \quad 0 \le T_{pul} \le T_p \,, \tag{1}$$

where T_{pul} – key-opening pulse duration, U_{cur} – measured output voltage, U_{et} – reference voltage, T_p – duration of the period of work (start) of the stabilizer.

Essentially, $F(U_{cur}, U_{et})$ maps the U_{cur} range to T_{pul} range:

$$[U_{cur}^{min}, U_{cur}^{max}] \Rightarrow [T_{pul}^{min}, T_{pul}^{max}], \tag{2}$$

where $U_{cur}^{min}, U_{cur}^{max}$ – minimum and maximum U_{cur} values, $T_{pul}^{min}, T_{pul}^{max}$ – minimum and maximum T_{pul} values.

The linear control law can be used in the simplest case [6-9],

$$T_{pul} = T_o + C\,(U_{et} - U_{cur}), \tag{3}$$

where T_o and C – undefined constants.

In general, the constant T_o can be defined as the value of T_{pul}, in which U_{et} is equal to U_{cur} (the required voltage is present at the stabilizer output). If we take into account the possibility of changing the load current in the range $I_{min} \div I_{max}$, so T_o is T_{pul} , in the case of an average load current equal to $(I_{min} + I_{max}) / 2$, $U_{et} = U_{cur}$, then

$$T_o = (T_{pul}^{min} + T_{pul}^{max}) / 2, \quad (4),$$

and, in the limiting case, when $T_{pul}^{min} = 0$, $T_{pul}^{max} = T_p$,

$$T_o = T_p /2. \quad (5)$$

The constant C determines the stabilizer sensitivity to U_{cur} variation:

$$dT_{pul} = -C\, dU_{cur} , \quad (6)$$

where dT_{pul} – pulse duration increment, dU_{cur} – output voltage increment,
and, at the same time, this constant is the scale of displaying the U_{cur} range to the T_{pul} range, so, different ratios of the ranges of U_{cur} and T_{pul} can be observed, as well as unused portions of these ranges, as shown in Figure 1.

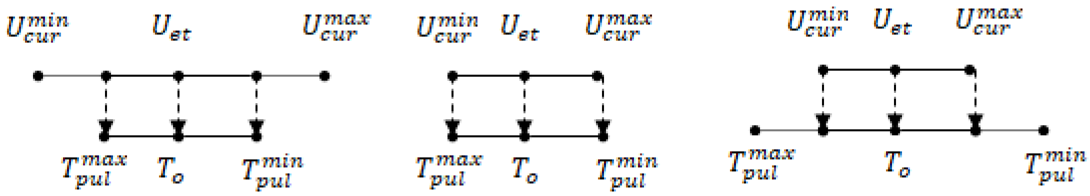


Figure 1. The ratio of the ranges U_{cur} and T_{pul}

In the case of using an analog control contour, voltages and durations are continuous, and, in the operating range, T_{pul} can be exactly calculated according to (3) for any combination of the values in the right side of the formula.

When organizing a control device in the digital form (Figure 2), a transition to discrete values, which have a limited number of values, occurs.

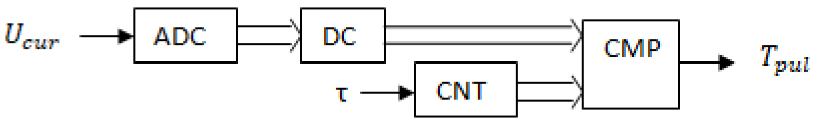


Figure 2. Digital control contour.

In the figure below, ADC is an analog-to-digital converter, DC is a digital calculator, CNT is a clock counter, CMP is a comparator, and τ is clock pulses. As can be seen in the figure, U_{cur} is the subject of analog-to-digital conversion, which leads to a deviation of the measured value from the true value by an amount of the Δ_U error, which, in turn, depends on the analog-to-digital converter (ADC) bit depth. U_{et} is converted to a constant from the set of the values, which being used to represent U_{cur}, and also contains the Δ_U error.

Figure 3 shows that T_{pul} in a digital circuit is being formed by counting clock pulses, and is actually being replaced by the nearest multiple of the clock pulse period, which leads to the Δ_T error, which depends on the duration of the clock pulse period, so, T_o turns into a constant from the set of the values from the T_{pul} representation, and also contains the Δ_T error.

Taking into account the discreteness of the values in the digital control contour, the control law (3) turns into

$$T_{pul} = T_o + C\,(U_{et} - U_{cur} + 2\,\Delta_U) + 2\,\Delta_T, \quad (7)$$

then the total error of the T_{pul} formation is estimated as

$$\Delta = 2\,C\,\Delta_U + 2\,\Delta_T. \quad (8)$$

The expression set out above shows, that the constant C began to influence not only the sensitivity of the stabilizer, but also the error of T_{pul} formation - with its decrease, the error produced by the analog-to-digital conversion decreases.

For an ideal ADC, the error depends on the ratio of the measured voltage range (scale) and the digit capacity of the resulting code.

$$\Delta_{adc} = \pm \frac{S_{max} - S_{min}}{2^{n+1}}, \qquad (9)$$

where S_{max} – maximum measured ADC voltage, S_{min} – minimum measured ADC voltage, n – bit width ADC.

To ensure correct display (2) under the condition of the minimum Δ_U error, it is necessary to match the ADC scale and the operating U_{cur} range

$$S_{max} = U_{cur}^{max}, \quad S_{min} = U_{cur}^{min}, \qquad (10)$$

so, Δ_U is estimated as

$$\Delta_U = \pm \frac{U_{cur}^{max} - U_{cur}^{min}}{2^{n+1}}. \qquad (11)$$

The Δ_T error, in accordance with (4, 5), is estimated as

$$\Delta_T = \pm \frac{T_p}{2\,N}, \qquad (12)$$

where N – the number of cycles in the period of the stabilizer.

Since U_{cur} takes one of the possible 2^n values in the discrete version, and T_{pul} turns into the number of ticks, then, to minimize the Δ_T error, it is necessary to have

$$N \geq 2^n, \quad (N - 2^n)/2 = 0, \qquad (13)$$

because, in this case, all 2^n values of U_{cur} can be accurately mapped to the corresponding number of the T_{pul} clock cycles symmetrically with respect to the T_o. If this condition is met, Δ_T goes to zero, and (8) turns into

$$\Delta = 2\,C\,\Delta_U. \qquad (14)$$

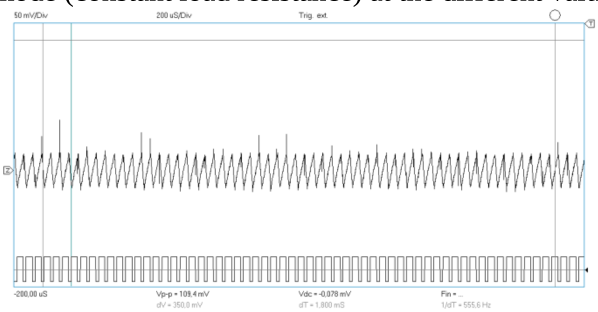
The C constant becomes the ratio of the ADC quanta number and the duration of the stabilizer period of operation in cycles in the discrete version

$$C = \frac{2^n}{N}, \qquad (15)$$

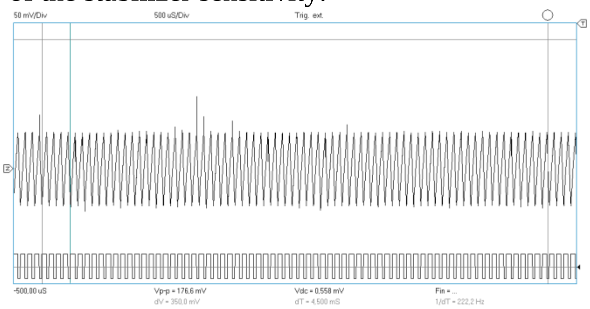
and therefore, in order to comply with condition (13), it should not exceed one, and, according to (15), the selection of the stabilizer sensitivity should be done by changing the number of ticks in the period of operation T_p in accordance with (13).

3. Experimental Results

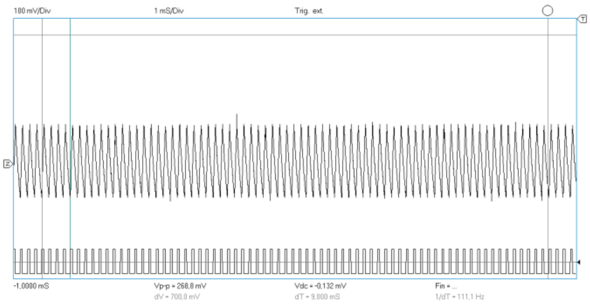
The correctness of the proposed behavior model of the pulse voltage stabilizer with a digital control contour, which uses the linear law (7), was tested on a model sample, described in [10,11], based on ATxmega128A1 microcontroller with a 32 MHz clock frequency and an ADC MAX1308 with n = 12 and ± 1 quantum error. Figure 3 shows oscillograms of the current flowing through the load in a static mode (constant load resistance) at the different values of the stabilizer sensitivity.



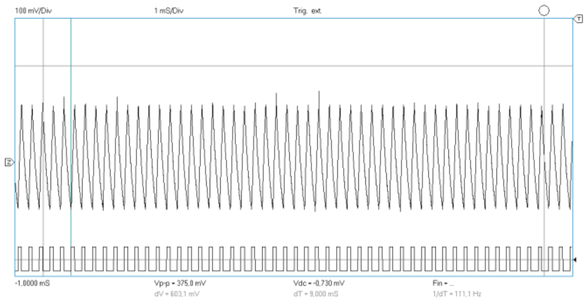
(a) Load current at C = 4



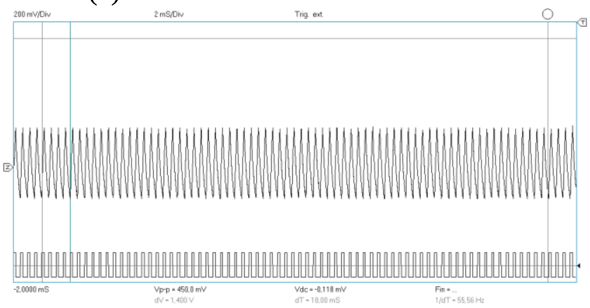
(b) Load current at C = 2



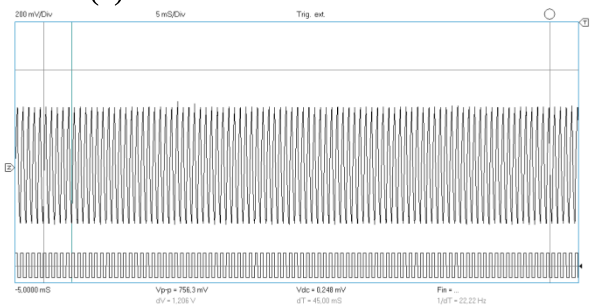
(c) Load current at $C = 1$



(d) Load current at $C = 0.75$



(e) Load current at $C = 0.5$

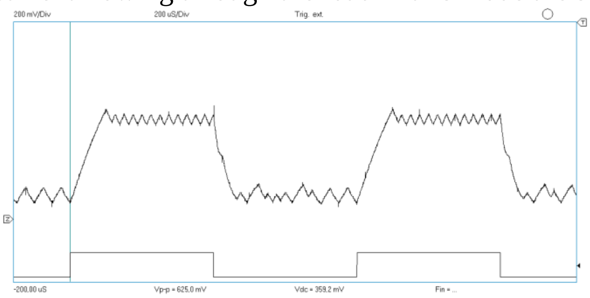


(f) Load current at $C = 0.25$

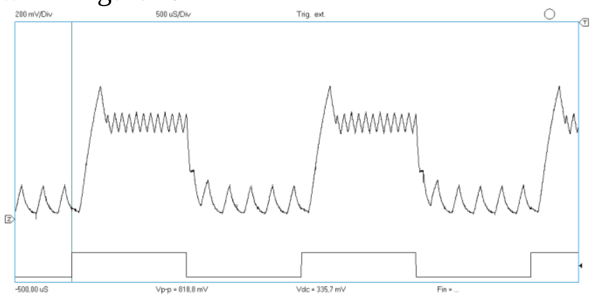
Figure 3. Waveforms of current through the load in static mode

The oscillograms in the lower part shows the control pulses of the stabilizer power key, in the middle part the current through the load. These oscillograms confirm the regularities presented in the model: at C = 4 a small oscillatory process is observed, which decreases with decreasing C and is practically absent at C = 0.25. On the other hand, a sufficiently large similarity between the oscillograms given above suggest that the model sample for the experiment contains ADC with a small error, that has little influence on the stabilizer operation, and this effect needs additional study.

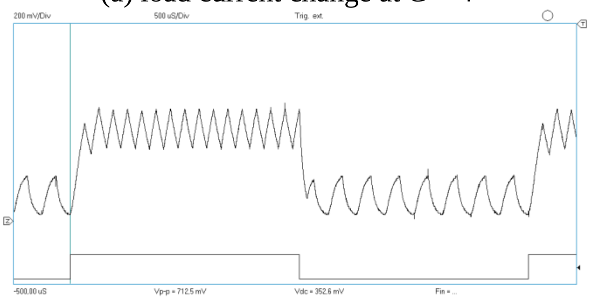
On the same prototype, the stabilizer was tested under conditions of a fourfold abrupt change in load resistance every sixteen periods of stabilizer operation (key control pulses). Waveforms of the current flowing through the load in this mode are shown in Figure 4.

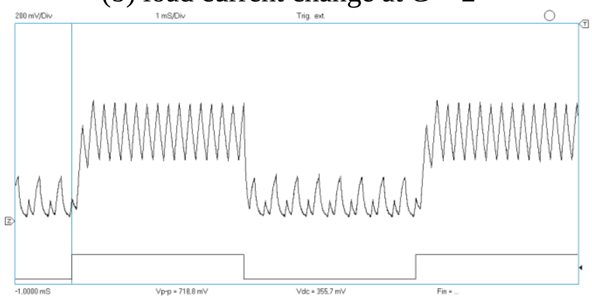


(a) load current change at $C = 4$



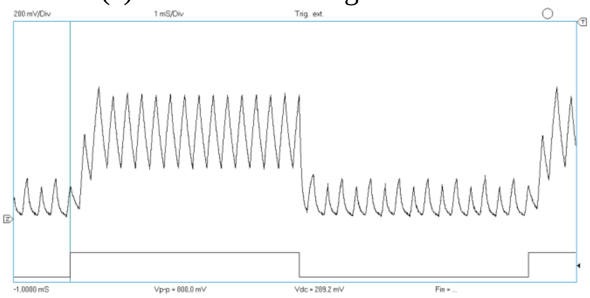
(b) load current change at $C = 2$



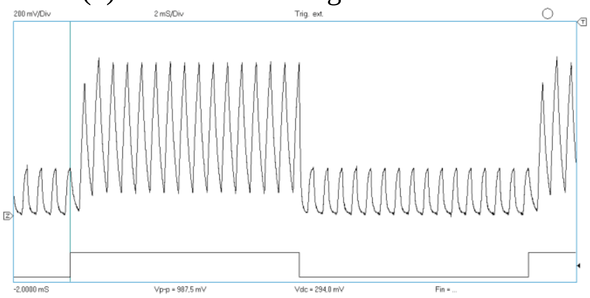


(c) load current change at C = 1

(d) load current change at C = 0.75



(e) load current change at C = 0.5



(f) load current change at C = 0.25

Figure 4. Oscillograms of current flowing through a varying load

The oscillograms in the lower part show the switching pulses of the stabilizer load, in the middle part - the current through the load. These oscillograms show that an increase in the C constant negatively affects the stabilizer operation, especially in areas with a low load, since they contain self-oscillations, which are decreasing with decreasing C, and practically absent at C = 0.25. The duration of transient processes (response time with the load changes) is small, but there is a small surge of the current, which appears when the mode reaches with the maximum load, and disappears with decreasing C.

4. Conclusion.

Conducted research presents an analytical model of the digital control contour of a pulse voltage stabilizer. The proposed model provides opportunities for improving the stabilizer operation by reducing the effect of errors in analog-to-digital conversion in the output voltage measuring circuit and in the transition to a discrete representation of the pulse duration for controlling the stabilizer power key in a whole number of cycles.

References

[1]Shtrapenin G. New generation of integrated circuits. National Semiconductor for switching power supplies. *Components and technologies*, 2007, no. 8, pp. 114–118. In Rus.

[2] *Analogovy mir Maxim. Novye mikroskhemy pitaniya* [Analog world of Maxim. New power microcircuits]. Moscow, Maxim Integrated Products Publ., 2014. No. 3, 60 p.

[3] Yuriy V. Krasnobaev, Oleg V. Nepomnyashchiy, Vladimir I. Ivanchura, Irina N. Pozharkova, Aleksey P. Yablonskiy, Pulsed Voltage Regulator with Digital Control for Autonomous Power Supply System / Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering. 2018. V. 329. 11. 61–73

[4] Yuri V. Krasnobayev, Denis V. Kapulin and Dmitriy V. Goncharuk Quick-Switching Voltage Regulator with Modular Principle and Discrete Control // Journal of Siberian Federal University. Engineering & Technologies 3 (2012 5) 327-339

[5] K. N. Tarchanidis, J. N. Lygouras and P. Botsaris Voltage Stabilizer Based on SPWM technique Using Microcontroller. Journal of Engineering Science and Technology Review 6 (1) (2013) 38-43

[6] Мелешин В. И. Транзисторная преобразовательная техника. М.: Техносфера, 2005.

[7] Tsypkin Ya.Z. *Teoriya lineynykh impulsnykh system* [Theory of linear impulse systems]. Moscow, Fizmatlit Publ., 1963. 968 p.

[8] Иванчура, В.И. Модульные быстродействующие стабилизаторы напряжения с ШИМ: Монография / В.И. Иванчура, Ю.В. Краснобаев. – Красноярск: ИПЦ КГТУ, 2006.

[9] Лукас, В.А. Теория автоматического управления: Учеб. для вузов. - М.: Недра, 1990.

[10] N.V. Titovskaya, S.N. Titovskii The Application of the Atxmega Micro-Controller in the Control Unit of the Pulse Voltage Stabilizer //Bulletin of KrasGAU.- 2015. - № 7 (106) 58 - 63.

[11] N.V. Titovskaya, S.N. Titovskii Organization of the Pulse Voltage Stabilizer Control Unit on the Micro-Controller Base // Bulletin of KrasGAU.- 2015. - № 8 (107) 87 - 92.